PERFORMANCE IMPROVEMENTS IN FREE SPACE OPTICAL LINKS WITH APPLICATION TO HIGH ALTITUDE PLATFORM COMMUNICATION SYSTEM

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PERFORMANCE IMPROVEMENTS IN FREE SPACE OPTICAL LINKS WITH APPLICATION TO HIGH ALTITUDE PLATFORM COMMUNICATION SYSTEM

by

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CERTIFICATE

This is to certify that the thesis entitled "**Performance Improvements in Free Space Optical Links with Application to High Altitude Platform Communication System"** being submitted by **Mr. MANISH** to the Department of Electrical Engineering, Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him. He has worked under our supervision and guidance. The thesis, in our opinion has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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ABSTRACT

In this thesis, we have proposed several solutions to achieve performance enhancements in free space optics (FSO) links. FSO can be used to provide high speed, high bandwidth secure communication to the end users. However, the performance of FSO links is dictated by the atmosphere. In order to enhance the performance, we have used combined MIMO-OFDM, channel coding with low-density parity-check (LDPC) code and serial relaying with FSO links.

MIMO uses spatial multiplexing and diversity to achieve higher capacity and robustness in communication links. OFDM is spectrally efficient and also, it provides a cost effective solution to improve the performance of communication links. The combined MIMO-OFDM is widely used in radio frequency (RF) communication. Hence, we have used MIMO-OFDM with FSO communication system to provide integration with currently existing technologies. In order to achieve higher capacities with MIMO-OFDM, spatial multiplexing is used in this work. Since, atmospheric turbulence can cause temporal broadening of the optical signal which results in inter-symbol interference (ISI). The performance of MIMO-OFDM FSO links has also been evaluated with ISI. To enhance the performance of MIMO-OFDM FSO links in terms of bit error rate (BER), we have used diversity with equal gain combining (EGC) at the receiver side. Closed form expression for the average BER of MIMO-OFDM FSO link is derived with EGC. Further, to increase the channel resistance, channel coding with LDPC codes has been used and performance is evaluated for different modulation schemes.

The performance of FSO can also be enhanced by scaling down the end-to-end link length by using a number of relays in between source node and destination node. This serial relaying also known as multi-hop communication has been studied extensively in this work with

the derivations of closed form expressions for the average BER, average channel capacity and outage probability. We have studied on-off keying (OOK) modulation and binary phase-shift keying (BPSK) subcarrier intensity modulation (SIM) with multi-hop FSO links.

As an application part of the work proposed in the thesis, we have used high-altitude-platforms (HAPs) to extend the range of FSO communication and also to provide communication facilities in difficult terrains of earth. The mathematical analysis of the performance matrices has been carried out and performance of multi-hop HAP with FSO has been evaluated. We also provide two reconfigurable architectures incase the communication disrupts due to atmosphere degrading or components failure. The reliability and availability analysis of the main architecture and proposed reconfigurable architectures has also been carried out, so that the FSO link designers can use the data obtained in this thesis for designing a complete FSO HAP architecture.

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LIST OF ABBREVIATIONS

4G	Fourth Generation
ADC	Analog to Digital Conversion
AF	Amplify and Forward
APD	Avalanche Photo Diode
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase-Shift Keying
CDF	Cumulative Distribution Function
CP	Cyclic Prefix
DAC	Digital to Analog Conversion
DF	Decode and Forward
EGC	Equal Gain Combining
EMI	Electromagnetic Interference
FFT	Fast-Fourier-Transform
FIT	Failures-in-Time
FSO	Free Space Optics
GS1	Ground Station 1
GS2	Ground Station 2
HAP	High-Altitude-Platform
HDTV	High-Definition Television
HV	Hufnagel-Valley

i.i.d	Independent Identical Distribution
IFFT	Inverse-Fast-Fourier-Transform
IM/DD	Intensity Modulation/Direct Detection
ISI	Inter-Symbol Interference
LD	Laser Diode
LDPC	Low-Density Parity-Check
LED	Light Emitting Diode
LLR	Log-Likelihood Ratio
LOS	Line-of-Sight
MGF	Moment Generating Function
MIMO	Multiple-Input Multiple-Output
ML	Maximum-likelihood
MMSE	Minimum Mean Square Error
MRC	Maximal Ratio Combining
MTBF	Mean-Time-Between-Failures
MTTR	Mean-Time-To-Repair
OAF	Optical Amplify-and-Forward
OEO	Optical-Electrical-Optical
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off Keying
ORF	Optical Regenerate and Forward
OSIC	Ordered Successive Interference Cancellation
OWC	Optical Wireless Communication

PAPR	Peak to Average Power Ratio
PDF	Probability Density Function
PPM	Pulse-Position Modulation
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
SC	Selection Combining
SIM	Subcarrier Intensity Modulation
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
STROPEX	Stratospheric Optical Payload Experiment
V-BLAST	Vertical Bell labs Layered Architecture for Space Time
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
ZF	Zero Forcing

LIST OF SYMBOLS

A	Amplitude of subcarrier signal
σ	Atmospheric attenuation (dB/km)
$\bar{\mu}$	Average electrical SNR
$\bar{\mu}_i$	Average electrical SNR of i^{th} hop
I_0	Average received intensity without turbulence
ρ	Average SNR at each receive antenna
P_t	Average transmitted optical power
B	Bandwidth
Θ	Beam parameter
C	Channel capacity
C_{AF}	Channel capacity with AF relaying
C_{DF}	Channel capacity with DF relaying
I_l	Channel fading due to atmospheric attenuation
I_a	Channel fading due to atmospheric turbulence
I_i^l	Channel fading of i^{th} hop due to atmospheric attenuation
I_i^a	Channel fading of i^{th} hop due to atmospheric turbulence
I_i^p	Channel fading of i^{th} hop due to pointing error
r	Code rate of LDPC code
I_i	Combined optical channel
$\dagger$	Conjugate transpose of matrix
α_i	Effective number of large-scale eddies of the turbulent atmosphere for i^{th} hop
α	Effective number of large-scale eddy parameter in gamma-gamma channel

	model
β_i	Effective number of small-scale eddies of the turbulent atmosphere for i^{th} hop
β	Effective number of small-scale eddy parameter in gamma-gamma channel model
μ	End-to-end instantaneous electrical SNR
w_{eq}	Equivalent beam width
ε_T	Error term in MIMO
K	Even number used to defines constellation
$E[.]$	Expectation
$H_{i,j}[n,m]$	Flat fading channel coefficient of (N×M)channel matrix
g_i	Gain of the i^{th} relay
$\Gamma(.)$	Gamma function
w_z	Gaussian beam waist at distance z
h	HAP altitude
$\tilde{E}_1$	IFFT transformation matrix
C_n^2	Index of refraction parameter
R_i	Information rate for the i^{th} hop
μ_i	Instantaneous electrical SNR of the i^{th}hop.
s_i	Instantaneous intensity gain of the i^{th} hop
$\mathcal{L}^{-1}(.)$	Inverse Laplace transform
σ_s	Jitter standard deviation at the detector
L_i	Length of i^{th} hop
L	Link length

V	Link visibility
l	Log-intensity of optical beam
$G_{p,q}^{m,n}(.)$	Meijer's G function
$K_v(.)$	Modified Bessel function of the second kind
α_T	Modified large-scale eddy parameter in gamma-gamma channel model
β_T	Modified small-scale eddy parameter in gamma-gamma channel model
ζ	Modulation index
$M_x(.)$	Moment generating function of x
I_M	MxM identity matrix
N_0	Noise power spectral density
n	Number of coded bits in LDPC coding
N	Number of FSO receivers in MIMO
M	Number of FSO transmitters in MIMO
N_h	Number of hops
k	Number of information bits in LDPC coding
N_f	Number of subcarriers in OFDM
Q	Number of symbols
I_N	NxN identity matrix
$P_{out}(.)$	Outage probability
$g(t)$	Pulse shaping function
a	Radius of photodetector
γ	Ratio of equivalent beam width to the jitter standard deviation
γ_i	Ratio of equivalent beam width to the jitter standard deviation for the i^{th} hop

R	Responsivity of photodetector
σ_R^2	Rytov variance
SNR_n	SNR of n^{th} subcarrier
σ_n	Standard deviation of the noise
ω_c	Subcarrier frequency in radians
μ_{th}	Threshold electrical SNR
λ	Wavelength
v	Wind speed